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Metallurgy Department

Progress Report
for the period 1 January to 31 December 1978

Risø National Laboratory, DK-4000 Roskilde, Denmark
April 1979

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METALLURGY DEPARTMENT PROGRESS REPORT FOR THE PERIOD 1 JANUARY TO 31 DECEMBER 1978

Abstract. The activities of the Metallurgy Department at Risø during 1978 are described. The work is presented in four chapters: General Materials Research, Technology and Materials Development, Fuel Elements, and Non-Destructive Testing. Furthermore, a survey is given of the department's participation in international collaboration and of its activities within education and training. A list (with abstracts) of publications and lectures by the staff during 1978 is included.

INIS-descriptors: FUEL ELEMENTS, METALLURGY, NON-DESTRUCTIVE TESTING, RESEARCH PROGRAMS, RISOE NATIONAL LABORATORY.

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INTRODUCTION

In 1978 it was politically decided to postpone for 2-3 years the decision concerning the establishment of nuclear power stations in Denmark. Risø is therefore still at stand-by, but most of the nuclear programmes have to be carried on in order to ensure continously up-to-date knowledge in the field. In the Metallurgy Department the nuclear work comprises projects within design, fabrication and testing of fuel elements, fracture mechanics studies in pressure vessel steels and non-destructive testing. The projects concentrate more and more on advanced problems, which in many cases is studied in collaboration with other parties in Europe and in the United States. Examples of such projects are ramp testing of fuel pins, computer modelling of fuel pin performance, dynamic fracture mechanics studies on steel and acoustic emission investigations of welds.

With respect to alternative energy technology, a major effort was devoted to fibre reinforced plastics, which have been chosen as wing-blade material for two 600 kW wind turbines built by a group of electricity generating companies. Six wings with a length of 12 meters each will be mounted in the spring of 1979. The department has participated in the wing development including fabrication studies, small scale and semi-scale mechanical testing and non-destructive testing. Other energy projects include metal-hydrogen systems (e.g. for transportation and storage of energy) and high temperature ion conductors; the latter project is carried out in collaboration with a group of Danish and British laboratories under the auspices of EEC.

Work has been done under contract for industries and utilities in Denmark and abroad. Due to their proprietary nature, most of these activities are excluded from the present report. Among the major activities were fuel element development, where collaboration with the Elsinore Shipyard was continued, isotope analysis and post-irradiation examinations of full-scale power-reactor fuel rods ($Zr-UO_2$ and $Zr-UO_2-PuO_2$). In the last two

areas, much of the work took place as part of an EEC programme on the recycling of plutonium in light-water reactors.

Other work on contract was done on high temperature components for the chemical industry and on acoustic emission for non-destructive testing purposes (the latter in collaboration with the Danish Welding Institute). Further projects were centered on the development of materials and processes, in particular ceramics for measurement of oxygen potentials in combustion gases, sintering of nuclear ceramics, and brazing technology. In the latter area, a joint programme with the Danish Welding Institute and the Corrosion Centre was carried out with the aim of finding substitutes for cadmium-containing silver alloys, in order to reduce industrial health hazards.

To support the technological programmes of the department a large effort was as usual devoted to fundamental problems e.g. radiation damage in metals, strength/structure relations in single-phase and two-phase materials and structures in ceramics. Solid electrolytes and hydrogen-metal reactions were taken up as new activities. A large part of the fundamental work is carried out in collaboration with universities and research laboratories in Denmark and abroad.

The department participated in international collaboration on specific research subjects and also in a number of international projects and study groups under the auspices of the NEA, EEC and various Nordic organizations.

The department arranged and hosted during 13-15 September the IAEA-IWG-RRPC specialist meeting "Repair Aspects and Procedures". The program of the meeting covered current experience with repair of reactor pressure components both at the fabrication and the construction stage and in service.

Educational activities were continued; students and post-graduates from Denmark and abroad studied in the department. One lic.techn. (Ph.D.) student passed his final examination during the year.

GENERAL MATERIALS RESEARCH

Deformation of composites

The mean field theory for the effective thermo-elastic and plastic deformation of multiphase composites was extended to cover the coupled and uncoupled linear equilibrium properties and the uncoupled linear steady-state transport properties. The equivalence of the mean field theory and the established variational theory was given a rigorous proof. The mean field theory confirms results suggested by earlier approximate calculations of workhardening and permanent softening in two-phase alloys consisting of a soft matrix phase with a low volume fraction of hard inclusions. The workhardening can be separated

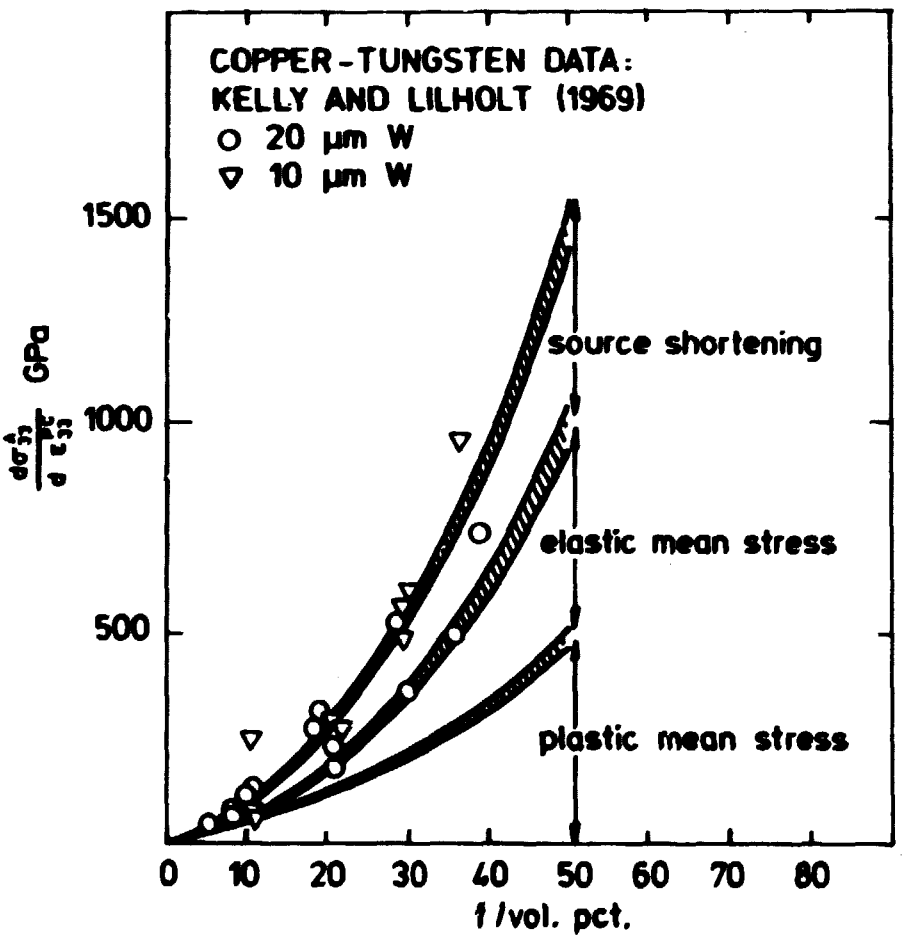

Fig. 1. Comparison of the theoretically predicted hardening contributions in copper-tungsten with experimental measurements.

into two major contributions: The irreversible frictional hardening (source shortening) and the reversible kinematical hardening (mean stress). For large volume fractions of hard phase the mean field theory shows that the mean stress in the stressed alloy consists of two comparable contributions: The plastic mean stress and the elastic mean stress. The elastic mean stress vanishes in the unstressed alloy.

Creep in FCC metals

Specimens of Cu-15% Zn were creep-tested at various stresses and temperatures. The creep tests were interrupted in the secondary stage, and the dislocation structures developed during the creep tests were examined by transmission electron microscopy for measurement of the dislocation distribution functions.

Measurements of the incubation period following a stress reduction during creep were initiated on specimens of pure Cu. Effective diffusion coefficients for creep can be derived from the measurements on the basis of a recently developed model for the incubation period, and the purpose of the experiment is to examine whether a contribution from dislocation pipe diffusion can be detected in this way.

Fatigue phenomena in copper

Single and polycrystals of pure Cu were cyclically deformed in tension/compression at constant low plastic strain amplitudes. For single crystals the single slip behaviour is as described in the literature. The cyclic hardening rate is higher for multislip orientations than for single slip orientations; but for all single crystals the cyclic deformation led to a surface pattern of persistent slip bands suggesting that mainly one slip system is active in the saturated condition. For polycrystals the cyclic hardening rate is comparable with that of the multislip oriented single crystals. Plots of the saturation stress versus plastic strain amplitude for polycrystals clearly show a

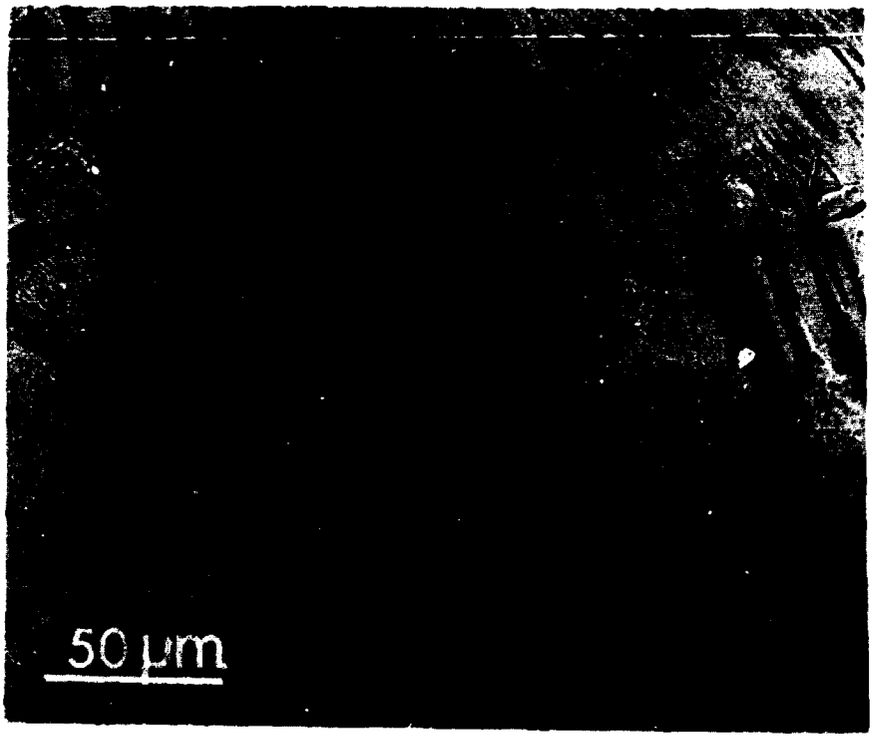

Fig. 2. Persistent slip bands on a copper polycrystal fatigued in tension-compression (19.000 cycles) with a plastic strain amplitude of $4 \cdot 10^{-4}$. Two active slip systems are seen.

plateau for amplitudes lower than 10^{-3} (stresses and strains are converted on the basis of the Taylor model). Above 10^{-3} the saturation stress increases with plastic strain amplitude.

Plastic deformation of polycrystals

Tensile-stress-strain data over a strain range from 0.2% to 30% were obtained at room temperature for 99.999% copper as a function of grain size. The flow-stress/grain-size relationship was analyzed in terms of matrix strengthening and grain boundary strengthening according to the dislocation concept of Ashby. At intermediate strains this approach gives a good description of the effect of strain and grain size on the flow stress.

The compatibility of the classical "macro-crystallographic" models for the plastic deformation of polycrystals, viz. the Taylor model and the Sachs model, with a description in terms of dislocations was considered. The Taylor model, as it is normally formulated, does not seem to be compatible with such a description. A modified Sachs model (in which multiple slip is accepted as a physical reality) appears to be a viable alternative to the Taylor model.

Acoustic emission

The factors affecting acoustic emission generated by brittle fracture of second-phase inclusions in a ductile matrix were studied. The system of W fibres in a Cu matrix was used as an experimental model system in which the size of the fracturing inclusions can be systematically varied. The brittle fracture of W fibres was experimentally correlated with acoustic signals. A theoretical model was developed and used to study possible factors influencing the size of the acoustic signals.

Radiation damage in stainless steel

(in collaboration with the Metallurgy Division, AERE Harwell, U.K.)

Thin foils of laboratory made "pure' austenitic stainless steel, resembling the commercial AISI type 316 steel, containing 0.25, 0.5, 1.0 or 2.0 wt% Si were irradiated in the Harwell High Voltage Electron Microscope. The irradiations were carried out at temperatures between 400 and 700°C. The void swelling parameters were determined quantitatively from micrographs taken at different doses.

The main effect of silicon addition is a progressive decrease in linear swelling rate with increasing silicon content at all irradiation temperature up to 600°C. The decrease in swelling rate resulted from a large decrease in void growth rate combined with a complex void density behaviour.

The "incubation" dose increased substantially with silicon content from $\sim$ 5 dpa in the base alloy to > 20 dpa with 2% silicon.

The formation of Ni_3Si precipitates was observed in the high silicon alloys in the temperature range 450-550°C.

Void nucleation

(In collaboration with the Metallurgy Division, AERE Harwell, U.K.).

We have used our theory for void nucleation based on Brownian motion to calculate the temperature dependence of the void density for an austenitic stainless steel under accelerator as well as reactor conditions. The Arrhenius plot of the calculated void density is found to consist of two linear segments with very different slopes, representing well defined intermediate and high temperature regions. The activation energy for the intermediate temperature region is found to be approximately 0.5 E_v^m, where E_v^m is the vacancy migration energy. It is also shown that the resulting activation energy for this region can vary appreciably due to several factors, e.g. the temperature dependence of the Brownian motion. The activation energy for the high temperature region is found to be much larger and to approach the activation energy for self-diffusion; this provides a high temperature cut-off to the void swelling.

In order to test these predictions, a review has been made of the experimentally determined temperature dependences of the void density for stainless steels and pure metals (f.c.c. and b.c.c.) irradiated under reactor and/or accelerator test conditions.

Dislocation climb and point defect profiles

It was shown theoretically that the E/E_V^M values lower than 0.5 reported in literature for copper (E being the apparent activation energy for loop growth during irradiation in the high voltage electron microscope (HVEM) and E_V^M being the vacancy migration energy) may be understood as an effect of the point-defect profile in the thin foil specimens. It was also shown that the divacancies, which have been suggested to be the cause of the E/E_V^M values lower than 0.5, do not have any great effect on loop growth in Cu under HVEM conditions.

Radiation experiments on cold-worked pure copper

(In collaboration with the Metallurgy Division, AERE Harwell, U.K.).

High purity copper was rolled at room temperature to thickness reductions of 10, 25, 50, 70 and 90%. The dislocation density was determined in the as-deformed materials by normal transmission electron microscopy. Thin foils of the different materials were irradiated in the high voltage electron microscope at 250, 300, 350 and 450°C, and quantitative analyses of voids and dislocations were made on micrographs taken at different doses.

The variation of swelling rate with the degree of cold work was determined at all four irradiation temperatures, initially the swelling rate increased with cold work, but beyond a certain degree of cold work the swelling rate started to decrease with further cold work. At irradiation temperature up to 350°C there was no indication that cold work could reduce void swelling to a level lower than that of annealed material. At 450°C, however, the swelling for the highest degrees of cold work was significantly lower than the swelling in annealed copper.

At all degrees of cold work and at all irradiation temperatures the average dislocation density decreased with increasing irradiation dose. At a given irradiation dose and temperature the average dislocation density remained higher in the materials cold-worked to higher degrees.

In order to understand the experimentally measured effects of cold-work on void formation, theoretical calculations have been initiated.

a

b

Fig. 3. It is frequently observed in HVEM-irradiated cold-worked copper that the void distribution is very inhomogeneous for high degrees of cold work (for which the swelling rate has started to decrease with increasing degree of cold work). For lower degrees of cold work the void distribution is rather homogeneous. (a) shows inhomogeneous void distribution in 90% cold-worked material irradiated at 300°C; the void distribution is obviously related to the substructure. (b) shows homogeneous void distribution in 25% cold-worked material also irradiated at 300°C.

Recrystallization in aluminium containing low volume fractions of small alumina particles

The kinetics of recrystallization were investigated in aluminium alloys containing low volume fractions of small oxide particles. Both the formation of recrystallization nuclei and their subsequent growth is retarded by the presence of the particles.

An investigation of the microstructural changes occurring during

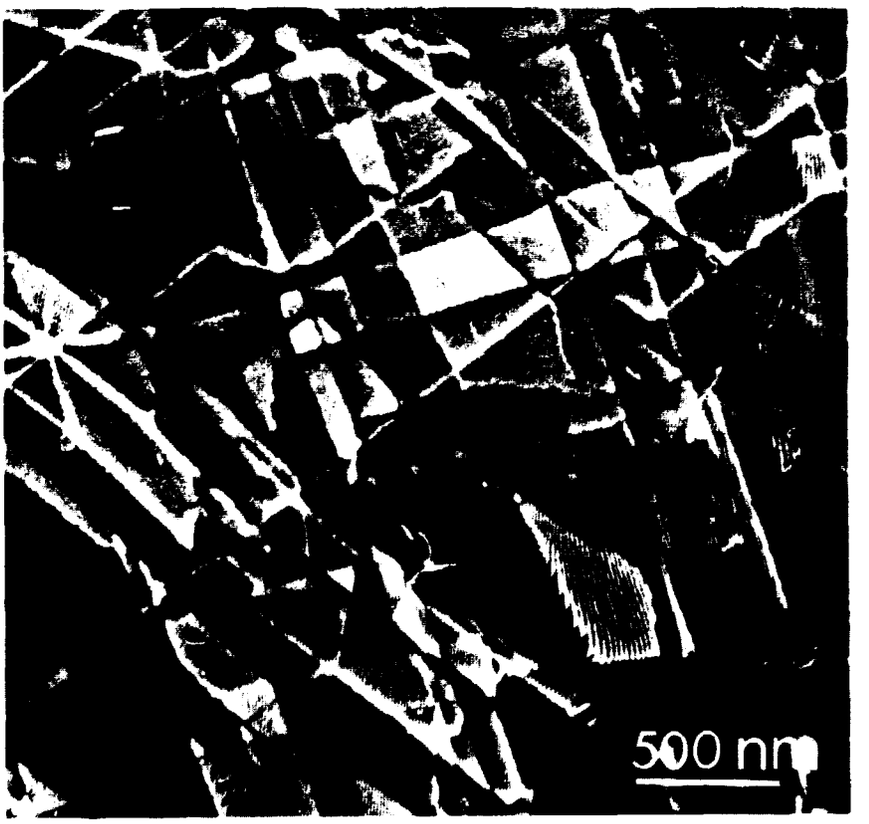

Fig. 4. Transmission electron micrograph showing a grain boundary in recovering aluminium. Both intrinsic and extrinsic grain boundary dislocations are present in the interface. The form of the extrinsic dislocations suggests that cross-slip has occurred during recovery.

recrystallization revealed that grain boundaries were preferential sites for the nucleation of new grains. Electron microscopy provided evidence of the link between subgrain coalescence processes and the formation of recrystallization nuclei at grain boundaries. On the basis of the microstructural observations, a model was proposed for the nucleation of recrystallization at grain boundaries. This model complements and extends the existing models for the nucleation of recrystallization.

As a further result of the above investigation, subgrain boundary structures are being investigated in an attempt to elucidate the nature of the mechanisms responsible for the retardation of nucleation of recrystallization by low number densities of small particles.

Recrystallization in aluminium of commercial purity

(In collaboration with the Danish Academy of Engineering, Copenhagen).

Experiments on the initial stages of recrystallization in commercial aluminium with a purity of 99.4% were made with the use of in-situ annealing in a high voltage electron microscope, transmission electron microscopy and light microscopy. It was found that the initial grain boundaries and high angle boundaries within the original grains are preferential sites for recrystallization nuclei and that the effect of such sites is enhanced by the $FeAl_3$ particles present in the commercial aluminium as impurities. The size of the recrystallization nuclei, the recrystallization temperature and the recrystallized grain size were determined in samples with an initial grain size of 19 or 370 μm and deformed 50% or 90% by cold rolling.

Kinetics of the hydrogen uptake in and release from Fe-Ti alloys

Equipment was constructed for the determination of reaction rates at constant temperature and pressure (-20 to +100°C and 1 to 50 atm.) for hydrogen uptake in and release from Fe-Ti alloys with the purpose of examining the kinetics involved in the reaction. The effect of second phase particles is of particular interest.

Samples of the composition $Fe_x\ Ti_{1-x}$ ($0.40 \leqq x \leqq 0.60$) were prepared and characterized with respect to phases and impurities before their use for the reaction rate measurements. They were found to contain about 0.04% oxygen but no significant amount of other impurities. Photomicrographs and X-ray analysis showed that the only phases present were FeTi, Fe_2Ti and Ti.

Substoichiometric oxide systems

(In collaboration with the Transuranium Institute, Karlsruhe).

Thermodynamic studies suggest the existence of a series of ordered phases in the non-stoichiometric range of the Ce-O and Pu-O systems. The defect structure of these phases can be described by a systematic packing of the three types of defect complexes shown in fig. 5. Each complex contains a "tetrahedral defect" consisting of one oxygen vacancy bonded to two reduced cations. Preliminary calculations were carried out on the basis of a statistical thermodynamic model which includes the concept of tetrahedral defects. The calculated thermodynamic data agreed fairly well with experimental data.

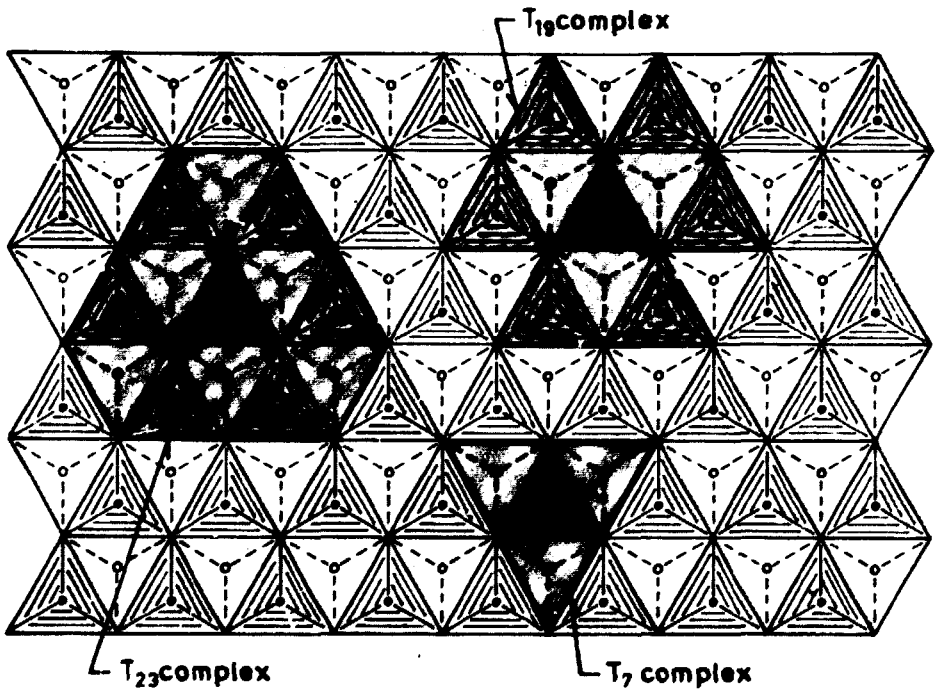

Fig. 5. Projection on (111) of the three types of defect complexes used to describe the structure of non-stoichiometric cerium- and plutonium oxides.

Fibre-reinforced plastics

Mechanical properties - including elastic constants, stress-strain behaviour, tensile strength, compressive strength - were measured for various fibre-reinforced materials. Theoretical studies were made of the mechanical properties of laminates with emphasis on their elastic constants. The results were used in several practical cases.

The department acts as consultant to the Electricity Generating Companies in connection with the building of power-generating wind turbines with financial support from the Ministry of Commerce and Industry. The consultancy concerns primarily materials for the wing-blades. These consist of a load-bearing internal spar and aerodynamic shells. The spar consists of a polyester matrix with glass fibres preferentially aligned parallel to the longitudinal axis of the spar. The shells are made of randomly oriented glass fibres in polyester, and, in regions, stiffened with balsa wood in a sandwich construction.

Fig. 6. Fabrication of glass-fibre/polyester spar by the winding technique.

The spar is fabricated by a special winding technique, where a woven glass fibre tape, soaked with polyester, is wound on to a steel mandrel. This method ensures well-aligned fibres and a satisfactory fibre volume fraction of more than 40 per cent. The shells are fabricated by hand-lay-up of glass mats in polyester in a three part mould. The wing is assembled by adhesive bonding.

The quality of the fabricated parts was examined by mechanical testing in tension, compression, shear and bending. Also, the density and glass content of the spar material was measured. In near full-scale experiments one spar and one wing section - both corresponding to the outer 6 meter of the wing - were elastically loaded in torsion and in bending and finally loaded to failure.

A prototype wing of 12 meters full length was fabricated. Tests showed satisfactory sectional stiffness and resonance frequency for the spar and the wing.

Metal-hydrogen systems

Compacted magnesiumpowder was exposed to hydrogen at 4.5 atm. and 340^{o}C. Despite the generally accepted difficulties in obtaining any spontaneous reaction under such conditions, a substantial although rather slow sorption (1.22 w/o in 48 hrs) was found.

The experiments were continued with pure magnesium under higher pressure and temperature (40 atm., 400^{o}C). The preliminary results may be summarized as follows:

(1) Hydride formation is completed in less than 4 hrs for powders with average grain sizes smaller than 150 μm.

(2) The specific surface area is to a first approximation rate determining.

(3) The hydrogen uptake is not hindered by the presence of a heavy oxide film on the particles.

(4) If the powder is compacted into pellets, the large lattice expansion will result in a complete disintegration after just one or two sorption cycles.

The easy formation of MgH_2 is not an incidential performance of one particular powder. The experiment was repeated with powder of a different manufacture with virtually the same results.
A cycling experiment (four cycles) showed an increase in reaction rate with number of cycles. This effect was observed in sorption as well as desorption.
Scanning electron microscopy (SEM) indicated that with cycling the particles turn into a spongy structure with increasing specific surface area. Also, SEM indicated that the oxide surface layer is heavily fissured (see fig. 7). This should give the hydrogen access to the metal surface.

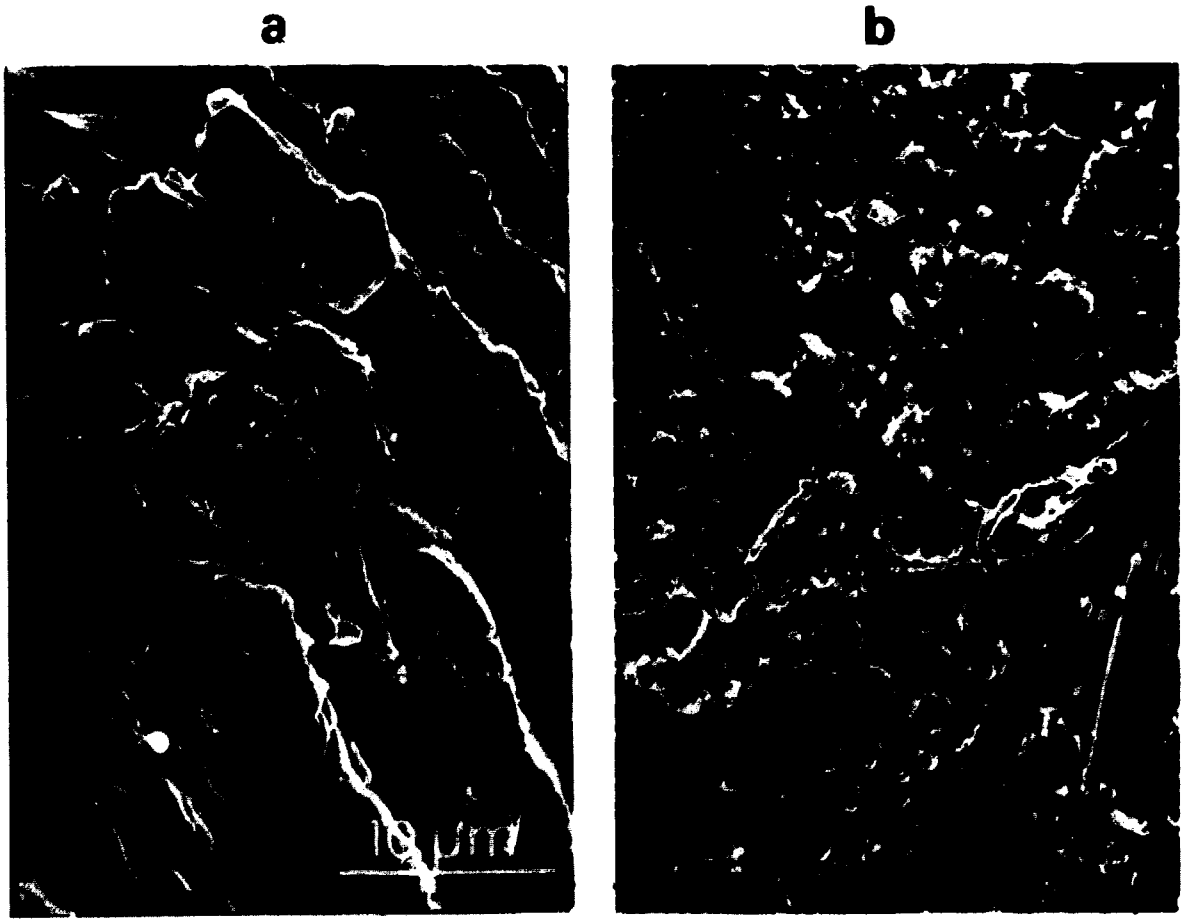

Fig. 7. Magnesium particle surface observed by scanning electron microscopy. (a) Before exposure to hydrogen. Note the heavily fissured oxide layer. (b) After hydrogenation. The scales are supposed to be pure MgH_2 formed in the initial stage of the $Mg-H_2$ reaction.

Oxygen sensing probe

A probe for measuring the oxygen content of furnace atmospheres or combustion gases has been developed. The probe is capable of measuring the oxygen content in the temperature range from a few hundred ^{o}C to well above 1000 ^{o}C with a response time of a fraction of a second. The probe has been successfully tested in a number of industrial furnaces (fig. 8).

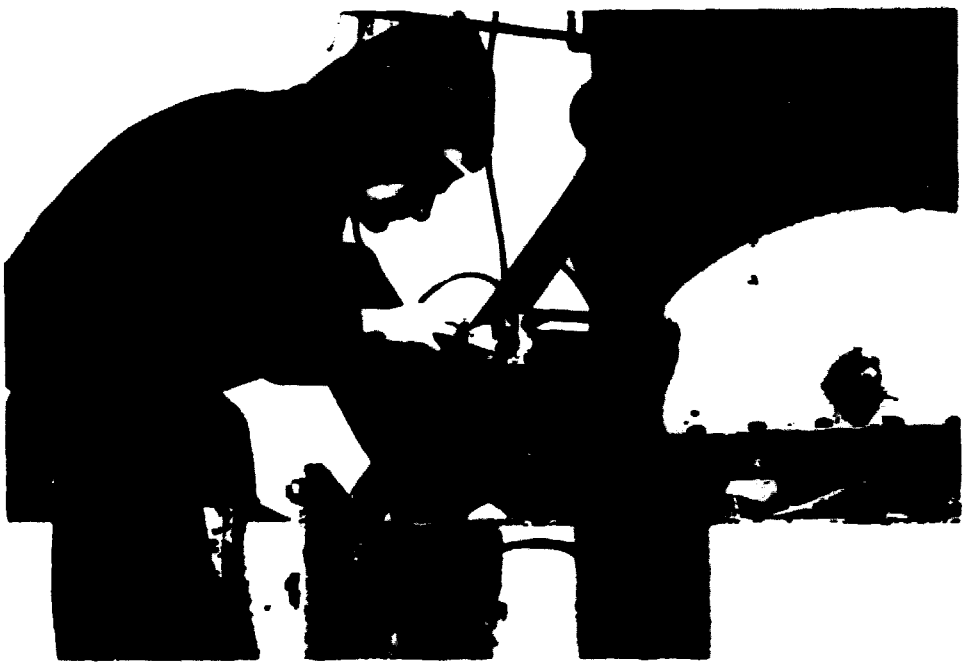

Fig. 8. Testing of the oxygen sensing probe in an industrial furnace.

Solid electrolytes

(EEC project in collaboration with A.E.R.E. Harwell,University of Leeds, University of Oxford, Imperial College (London), Odense University and The Technical University of Denmark).

Work was started to examine the conductivity of electrolytes in the CeO_2-Gd_2O_3 system, which have been reported to be good oxygen ion conductors at relatively low temperatures. The optimum conditions for production of thin discs of this material were studied.

The production of a promising electrolyte based on LiI and Al_2O_3 was investigated in spraydrying and vacuumdrying experiments. The lithium ion conducting phase was found to contain hydrate water. Details of the conduction mechanism is under examination by neutron scattering, NMR and ac-conductivity methods.

Samples of $LaAlO_3$ prepared at Leeds University for use as solid electrolytes were examined by transmission electron microscopy for the possible presence of a second phase and its distribution.

$LaAlO_3$ undergoes a phase transition from a cubic to a rhombohedral structure at around 500°C. As a result of this, the material exhibits a domain structure at room temperature. A new and easy method for determination of the orientation of the individual domains by diffraction contrast was developed.

Machining of carbon-fibre reinforced plastics

The hardness and the abrasive properties of carbon fibres make the machining of carbon-fibre reinforced materials with chip-forming tools very difficult. A project was started to investigate the mechanisms of the chip-forming process in order to find guidelines for better machining of these composites.

Fatigue of composite materials

A study was initiated to describe the fatigue of composite materials in terms of the changes in their stiffness properties. A new type of specimen which will allow the measurement of changes in all the stiffness constants was designed.

Fracture toughness of steel A533B

The statistical scatter of the fracture toughness of steel A533B - a grade often used in pressurized water reactors - is investigated. Both base metal and welds are considered. The attenuation of ultrasonic waves in different parts of the welds was measured and attempts are made to correlate this property to the toughness, so that toughnerss of welds can be made with NDT-equipment.

Two different procedures for the measurement of the crack arrest capability of steel A533B are being examined. The programme is carried out under the auspices of the American Society for Testing and Materials and involves 30 laboratories throughout the world.

Materials testing

A fixture was constructed for the tensile testing machine for use in measurements of the shear modulus of anisotropic materials (e.g. fibre composites). The calibration of the relation between the load and the shear stress in the specimen was made by photoelastic measurements. The shear modulus was measured for materials used in wind mill beams. The results agreed well with full scale tests on the wind mill beams and with theoretical values.

Fig. 9(a). Metal dusting attack on a small tube of austenitic stainless steel AISI 321.

Fig. 9(b). Cross section of pitted area in the tube shown in (a). The surface is covered with a 40 μm layer of corrosion products and the grain boundaries are heavily carburized.

Metal dusting

A special type of localized high temperature attack, the so-called "metal dusting" has been studied. Metal dusting is a form of metal deterioration that occurs in gases containing carbon monoxide and/or hydrocarbons at temperatures usually in the range of 400-900°C. Many of the usual high temperature alloys, including the austenitic stainless steels, alloy 800 and nickel alloys as Inconel 600, are susceptible to this form of deterioration which most frequently appears in the form of pitting. The pits which often contain a magnetic powder of corrosion products (graphite, metal carbides and oxides) are severely carburized and accelerated carburization is considered the active reaction.

The phenomenon is illustrated in fig. 9 which shows a severe metal dusting attack on stainless steel AISI 321 by a gas (20% CO, 1% CO_2, 1% CH_4, 78% H_2) at about 800°C.

Brazing and Soldering

A joint project was started to investigate various cadmium-free silver brazing metals for use on steels and copper, since a revision of the Danish legislation on occupational hygiene has imposed very strict limitations on the use of cadmium-containing silver brazing metals. In this project, the wettability and the mechanical properties are investigated by this department, the corrosion from fluxes and flux residues by the Danish Corrosion Centre, and the fumes developed during flame brazing by the Danish Welding Institute.

Investigations on the improvement of the wettability by a zirconium getter on nickel-brazed Al- and Ti-alloyed high temperature materials were continued. It is studied how the strength of the brazed joints varies with different brazing gaps and nickel-based filler metals, and the results are compared with results obtained on similar specimens, gaps and filler metals, but with other and more time-consuming pretreatments of the same pure metal.

The contract work on industrial applications of dip-brazing, vacuum brazing and ultrasonic soldering of aluminium was continued.

In-pile corrosion testing

Specimens of dispersion-hardened zircaloy-2 were tested under BWR conditions for six reactor periods in the corrosion test rig in DR 3. The specimens were examined in the hot cells but the results are not yet available.

A new test series with SCANUK alloys (various experimental Zr-alloys) was started. These alloys have been tested earlier under simulated BWR conditions, but the oxygen concentration in the water turned out to be higher than normal. In the present tests (as well as in the tests of dispersion-hardened specimens) the control with the water chemistry was improved, so that a more appropriate oxygen concentration was obtained.

FUEL ELEMENTS

The Danish fuel elements in the Kahl and Halden reactors continue to perform well and to demonstrate the adequacy of the design and manufacturing processes.

The irradiation of UO_2-Zr fuel pins in the DR 3 reactor at Risø includes standard BWR and PWR type tests irradiated to very high burn-ups. Special tests such as power ramp tests are also being made.

Additional information on fuel performance becomes available as a result of international collaboration arrangements, i.e., the OECD Halden Reactor Project (Norway), the "Interramp" (BWR fuel) and the "Overramp" (PWR fuel) projects at Studsvik (Sweden), the information exchange with the NRC (USA), and the EEC sponsored activities (Brussels) relating to Pu recycling in LWRs.

Danish fuel element irradiations in the Kahl and Halden reactors

The four Danish fuel elements in the German BWR power reactor went on power for the first time in 1975. Irradiation was continued and these elements have now achieved an estimated average burn-up of 11,100 MWD/t UO_2. Two short test fuel pins, manufactured from the same UO_2 and Zr materials as the Kahl fuel pins, have now reached a burn-up of 28,900 MWD/t UO_2 in the DR 3 reactor.

Irradiation of the five test fuel elements in the Halden reactor (Norway) was continued. They have now reached the following estimated burn-ups (average assembly, after correction for fuel depletion):

IFA no.	148	161	165	201	202
MWD/t UO_2	31,400	32,600	29,900	25,400	22,400

The maximum local burn-up of 39,200 MWD/t UO_2 was achieved with IFA 161.

UO_2-Zr irradiations at Risø

In the test fuel irradiation programme at DR 3, standard fuel pins have reached maximum burn-up levels of 49,600 and 43,400 MWD/t UO_2 for BWR and PWR fuel, respectively.

High burn-up fission gas release data are available for five test fuel pins, irradiated to burn-up levels around 26,000 and 38,000 MWD/t UO_2. The three pins at the lower burn-up level were ramp tested without failure before unloading. All five pins had a helium content exceeding that of the fabrication backfilling; the increase could be attributed to a combination of ternary fission yield and alpha-decay of ^{242}Cm. The power histories were obtained routinely by calorimetry and qualified by destructive analysis. Mass- and alpha-spectrometry in combination with the isotope dilution technique were used to obtain the uranium and transuranium isotopic compositions as well as the content of the fission product ^{148}Nd. Together with axial gamma scans, this provided average pin burn-up for direct comparison with the calorimetric data. The agreement was within a few percent (relative). The five fuel pins are thus well characterized throughout design, fabrication, irradiation and post-irradiation examination. This makes them suitable for fuel performance code validation.

In another ramp test, which resulted in cladding failure, a Ge-Li solid-state detector with the necessary date acquisition system was mounted at the primary coolant outlet. A large number of detailed gamma spectra were collected at short time intervals to provide information on the time variation in the short-lived fission product escape from the failed fuel pin.

Fig. 10. Example of extensive fuel-clad chemical reaction in a PWR-type ramp-tested fuel pin. The appearance strongly suggests that there was full contact between pellet and cladding in the hot condition. The fuel is marked F, the cladding is marked C, and the reaction product is marked R.

The continued evaluation of the special low-interaction UO_2 pellet design LOWI (see previous annual reports) included a ramp test as well as two irradiations (LOWI vs. standard pellet) with central fuel thermocouples.

An unfuelled zircaloy cladding tube was mounted with several external strain gauges and irradiated to fast neutron fluences exceeding 10^{20} n/cm^2 to provide information on irradiation-induced changes in the gauge characteristics. This was done in preparation for an experiment in which local cladding deformation during irradiation of a fuel pin are to be measured with strain gauges.

Computer modelling of fuel pin performance

The Danish fuel performance code WAFER-3 can now simulate a full-length fuel pin with any given axial power profile. The current fission gas release models have been supplemented with a new release model with improved capability of analysing high-burn-up cases with power increases late in life.

The code has been used extensively and with good results for prediction and analysis of experiments from the Danish ramp test program and the internationally sponsored Interramp project at Studsvik (Sweden).

NON-DESTRUCTIVE TESTING

The projects in this field deal with the development and application of non-destructive techniques for various testing purposes.

X-ray radiography

As a result of a comparison of the image quality of paper and film in X-ray radiography, paper radiography is now currently used for the quality control of MTR fuel elements. It is attempted to introduce this technique in other fields of X-ray control.

Soft X-ray radiography of carbon-fibre reinforced composites was established as a routine technique, and densitometric scanning of X-ray radiographs was used to assess the properties and the quality of some industrial samples of a fibre reinforced material.

Neutron radiography

Nitrocellulose film (track-etch technique) and X-ray film (direct and transfer method) were used in an investigation of the image quality and the accuracy of dimension measurements on neutron radiographs. Fig. 11 shows typical defects found in fuel pins by neutron radiography.

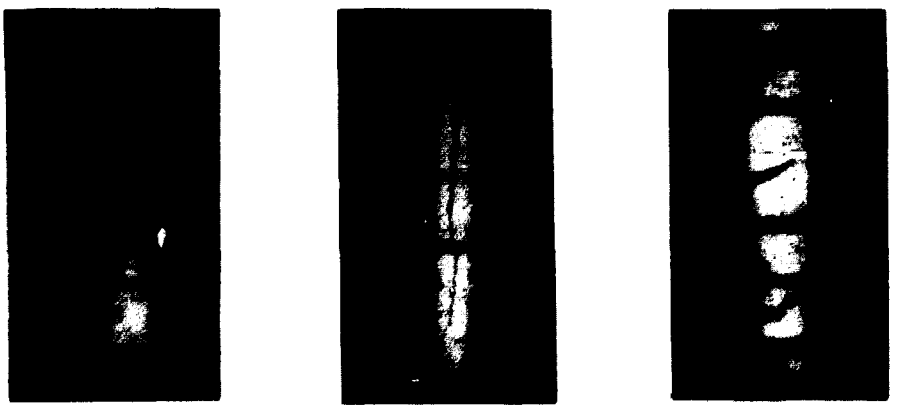

Fig. 11. Defects in fuel pellets revealed by neutron radiography. (a) Random cracks. (b) Longitudinal cracks. (c) Transverse cracks.

In order to standardize the neutron radiography of nuclear fuel, a program was initiated to expose a special calibration fuel pin in neutron radiography installations at Risø and in U.S.A., Canada and France.

Ultrasonic inspection

The work was concentrated on the design and building of a computerized scanning system. The system was designed for two different purposes:

(1) A three-dimensional scanning of a small volume for recording of sound waves from ultrasonic transducers.

(2) A two- (or three-)dimensional system for scanning of larger areas or volumes. This system can be operated under immersion conditions.

A series of welds in very thick steel plates was examined by means of the latter system.

NDT in hot cells

A new combined fixture for NDT inspection of fuel pins in the hot cells is under fabrication. The existing test modules for diameter measurement are being extended to give double independent determinations of diameter and radius. Test modules for eddy current testing with encircling coil technique as well as with pencil probe technique are being manufactured.

The fixture will be equipped with two independent systems for the measurement of rotational position and three independent systems for the measurement of axial position. Important information of the behaviour of the Inductosyn position measurement system in high gamma fields is expected from this design.

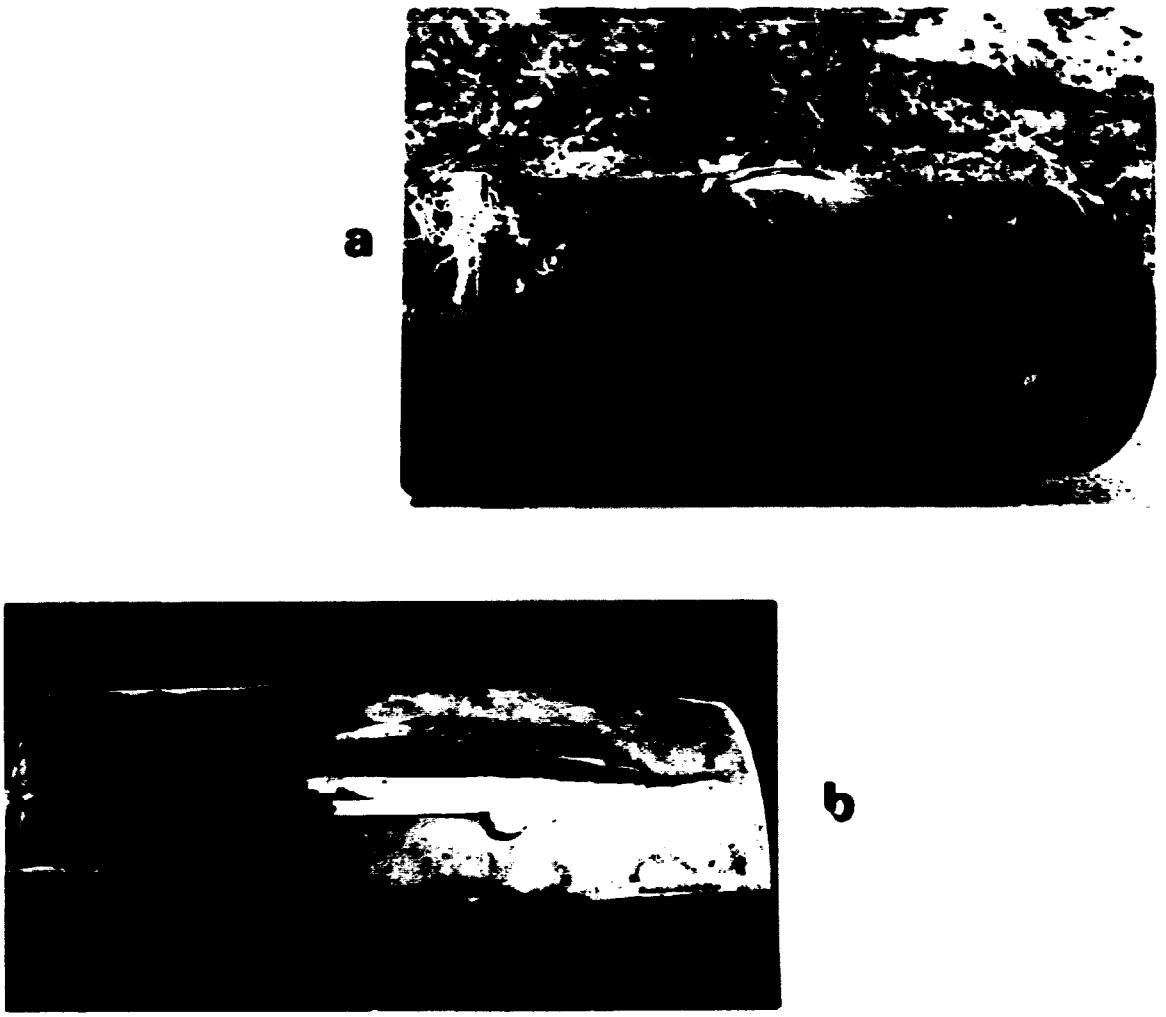

Fig. 12. (a). A test vessel after pressurization to fracture. The vessel was made from a 15 mm plate. It is 1 m long and ½ m in diameter. (b). Fracture appearance after pressurization. The fracture origirated from a slit in the weld and extended into the base plate before arrest.

Acoustic emission from medium-sized vessels

Medium-sized vessels were pressurized to fracture in order to assess the effect of a large crack tip constraint on the acoustic emission generated during deformation. The tests supplement tests performed on small specimens in the laboratory. Large structures attenuate acoustic emission signals more than small laboratory specimens do. The effect of this was also assessed.

Acoustic Emission

A research program into the application of acoustic emission to steel structures was completed. The object of the research was to characterize the acoustic emission generated by deformation and fracture processes associated with crack propagation in two mild steels of grade HII (DIN 17155) and 52-3 (DIN 17100) and in welds associated with submerged arc welding, CO_2 welding and manual arc welding with covered electrodes.

Acoustic emission analysis was carried out principally on the basis of signal amplitude distributions and the relationship between the acoustic emission, fracture behaviour and microstructure was investigated.

The following major conclusions were reached:
(1) Slow crack propagation in both base plate types is acoustically quiet.
(2) Slow crack propagation in weld metal generally gives larger amounts of emission than the same process in the base metal.
(3) Slow crack propagation in a submerged arc weld in base plate 52-3 generated substantially more emission than in the corresponding weld in base plate HII even though this weld has a high Charpy V-notch transition temperature of $-5^{\circ}C$ compared with that of $-80^{\circ}C$ for the welding plate 52-3.

PARTICIPATION IN INTERNATIONAL COLLABORATION

The department is engaged in the following types of international collaboration: joint technical projects, committee work, reception of research fellows, and technical and scientific meetings. Participation in the OECD reactor project at Halden was continued. Six Danish fuel elements are at the moment being tested under irradiation in the Halden reactor.

A joint technical project concerning the irradiation in the DR 3 of zircaloy-clad uranium-dioxide/plutonium fuel rods was continued (with the Studsvik Energiteknik AB, Sweden). Work was also continued on the joint programme for examination of advanced zirconium alloys for water reactors (with the UKAEA, United Kingdom, Studsvik Energiteknik AB, Sweden, IFA, Norway, and the Finnish AEC). Staff members took part in a Scandinavian working group on hot cell techniques.

The department was represented on the following committees:

The Information Exchange Group under the European Space Agency on Carbon Fibre Reinforced Plastics,

The Halden Programme Group,

The IAEA International Working Groups on "Reliability of Reactor Pressure Components" and "Water Reactor Fuel Performance and Technology".

The "Interramp" and the "Overramp" Project Committees,

The OECD/EEC Nuclear Energy Agency's Committee on the Safety of Nuclear Installations (NEA-CSNI) Working Group on Safety Aspects of Steel Components in Nuclear Installations,

The Working Group "Nuclear Corrosion" under the "European Federation of Corrosion",

The EEC Advisory Committees for Programme Management: "Plutonium and Transuranium Elements", "High Temperature Materials" and "Plutonium Recycling in Thermal Reactors",

The Council of the International Confederation of Thermal Analysis,

The Nordic Committee for Thermal Analysis,

and in the Technical Commission of the International Institute of Welding, Commission I, "Gas Welding and Allied Processes", Subcommission A, "Brazing and Surfacing".

EDUCATION AND TRAINING

N. Hansen and K. Rørbo gave regular lectures on materials science to students at the Danish Academy of Engineering. C.P. Debel, T. Leffers, H. Lilholt, O. Bøcker Pedersen, K.V. Rasmussen, K. Rørbo, and B.N. Singh lectured on physical materials science to students at the Technical University of Denmark. N. Hansen, T. Leffers, and H. Lilholt acted as external examiners at examinations for the Technical University of Denmark.

One scholarship holder from India worked in the Department on projects in the field of post-irradiation examination.

Post-graduate projects

Two post-graduate students from the Technical University of Denmark and one from the University of Copenhagen worked in the Department on the following projects in preparation for their licentiate (Ph.D.) theses:

A. Schrøder Pedersen:	Kinetics of the hydrogen uptake in and release from Fe-Ti alloys,
A. Koplev:	Machining of fibre-reinforced plastics,
K.V. Rasmussen:	Fatigue Phenomena in Copper.

Degrees conferred

The Technical University of Denmark conferred the degree of lic.techn. (Ph.D.) on P. Brøndsted.

PUBLICATIONS

Metallurgy Department Progress Report for the period 1 January to 31 December 1977.

Risø Report No. 377 (1978) 47 pp.

The activities of the Metallurgy Department at Risø during 1977 are described. The work is presented in four chapters: General Materials Research, Technology and Materials Development, Fuel Elements, and Non-Destructive Testing. Furthermore, a survey is given of the department's participation in international collaboration and of its activities within education and training. A list (with abstracts) of publications and lectures by the staff during 1977 is included.

Details of Design, Irradiation and Fission Gas Release for the Danish UO_2-Zr Irradiation Test 022.

C. Bagger, H. Carlsen and P. Knudsen, Risø-M-2152 (1978) 14 pp.

Test 022 comprised three UO_2-Zr test fuel pins which were irradiated in the DR 3 reactor at Risø at 7.2 MPa (70 ato) system pressure. A burnup of approximately 3530 GJ/kg U (36,000 MWD/te UO_2) was accumulated at heat loads in the range 35 to 53 kW/m (350 to 530 W/cm) (test avg. values). Fission gas analysis for two of the pins showed that the releases were 48 and 36%. The experimental data are presented in sufficient detail for use in the validation of fuel performance codes.

A Theory for the Incubation Period Following a Stress Reduction During Creep.

J.B. Bilde-Sørensen, Phil. Mag. A 38 (1978) 1-13.

A dislocation model is presented for the phenomena following a stress reduction during creep. It is suggested that an incubation period for the production of new mobile dislocations arises because attractive junctions on the verge of breaking just before the stress reduction are no longer so after the stress reduction. The breaking stress of the junctions must be lowered by climb movements in the surrounding network before the junctions can break and release new mobile dislocation. On the basis of these concepts, an expression is derived for the length of the incubation period. This theoretical incubation period is much shorter than the time needed to establish an equilibrium structure at the new lower stress. The dependence of dislocation line tension upon line length is taken into account; as a result of this, recovery rates are predicted to depend on stress to a power larger than three. The theoretical predictions are in agreement with experimental data from the literature.

Preparation of Dispersion-Hardened Copper by Internal Oxidation.
P. Brøndsted and O. Toft Sørensen, J. Mater. Sci. 13 (1978) 1224-1228.

Internal oxidation experiments in CO_2/CO atmospheres on Cu-Al alloys for preparation of dispersion-hardened Cu are described. The oxygen pressures of the atmospheres used in the experiments were controlled with a solid electrolyte oxygen cell based on ZrO_2 (CaO). The particle size distributions of the Al_2O_3 phase obtained in the oxidation experiments show that good reproducibility can be obtained with this method, both for specimens oxidized in the same run and for specimens oxidized in different runs under nominally identical conditions. The experiments also indicate that particle size increases with decreasing oxygen pressure of the atmosphere.

Lodning af rustfaste stål uden flus. (Fluxless Brazing of Stainless Steels).
J. Christensen, Dansk Tekn. Tidsskr. 102 No. 2 (1978) 10-14.

Furnace brazing of stainless steels gives many advantages such as stress-free components in which the joints are tight, smooth, and corrosion resistant. The components are bright-annealed and come out of the furnace with a bright surface free from any discolouration. In a dry hydrogen atmosphere or in a high vacuum all surface oxides will be removed at the brazing temperature; this leaves the metal surfaces in the joints in a condition for perfect wetting. Since corrosive chemical fluxes are not used, no cleaning operations are needed after the brazing.

Lodning af metal-keramik. (Brazing of Metal-Ceramics).
J. Christensen, In: Svejsning og Lodning, Proceedings of Dansk Metallurgisk Selskabs Vintermøde, Lyngby, 5-6 January 1978. Edited by E.W. Langer and T.S. Nielsen. (Dansk Metallurgisk Selskab, Lyngby, 1978). Insert 9 pp.

A short survey is given of the basic problems encountered in the brazing of ceramics (eg. Al_2O_3) to metals: physical and mechanical properties, design and wetting. Brazing procedures and filler metals are given for premetallized ceramics (Mo-Mn process) as well as for direct wetting of the ceramics.

Brudmekanisk vurdering af revner i svejste konstruktioner. (Fracture Mechanics Assessment of Cracks in Welds in Structural Steels).

C.P. Debel, In: Svejsning og Lodning, Proceedings of Dansk Metallurgisk Selskabs Vintermøde, Lyngby, 5-6 January 1978. Edited by E.W. Langer and T.S. Nielsen. (Dansk Metallurgisk Selskab, Lyngby, 1978) 107-131.

The concept of the Crack Opening Displacement (COD) method is presented. This method enables an elastoplastic fracture mechanics assessment of crack stability for cracks embedded in structural steels and in welds in such steels. Examples of stability calculations are given.

Non-Destructive Control of Carbon Fibre Reinforced Composites by Soft X-ray Radiography.

J.C. Domanus and H. Lilholt, In: ICCM/2, Proceedings of the 1978 International Conference on Composite Materials, Toronto, Canada, 15-20 April 1978. (Metallurgical Society of AIME, New York, 1978) 1072-1092.

The usefulness of the radiographic technique to the examination of carbon fibre reinforced composites was investigated with soft X-rays. The exposure technique was established for the radiography of 2 and 3 mm thick samples. A constant mAmin technique was used, by which radiographs of an approximately constant density were produced on different brands of X-ray film and paper at voltages of 10 to 17 kV.

The quality of the radiographs was checked by using a step wedge and measuring density differences under it. Accuracy with which dimensions can be determined from the radiographs was checked by use of samples with thin tungsten wires. Defect detectability was investigated by examining the radiographs of samples with natural defects.

It was proved that low voltage radiography with soft X-rays is particularly suitable for the non-destructive examination of carbon fibre reinforced composites.

Comparison of X-ray Film and Paper Radiography.

J.C. Domanus and C.Mikkelsen, In: Recent Developments and Special Methods of NDT, Proceedings of the First European Conference on Non-Destructive Testing, Mainz, 24-26 April 1978. (Deutsche Gesellschaft für Zerstörungsfreie Prüfung, Berlin, 1978) 593-601.

In many fields of industrial radiography, radiographic paper can be used instead of X-ray film. This has the advantage of being about three times cheaper and giving ready-to-use results in much shorter processing time. To prove the usefulness of radiographic paper, characteristic curves, relative speed, contrast and exposure latitude as well as the quality of the radiographic image for aluminium, steel and uranium/aluminium alloy were investigated. Exposure charts for Al and Fe were also compared.

Materialeforskning og Energiteknologi. (Materials Research and Energy Technology).

N. Hansen, Jernkont. Ann. No. 3 (1978) 16-20.

The research in the Metallurgy Department is reviewed under the following headings: 1) fuel elements for power reactors, 2) fuel elements for research reactors, 3) steels for pressure vessels, 4) fibre glass propellers for wind mills, 5) non-destructive testing, 6) metal-hydrogen systems, and 7) basic research within the field of materials science.

Recrystallisation of Metals and Alloys Containing Dispersed Particles.

N. Hansen, In: High Performance Materials and Processes, Proceedings of the Danish-Israeli Conference, Lyngby, 14-17 August 1978. Edited by E.W. Langer and T.S. Nielsen. (Dansk Metallurgisk Selskab, København, 1978) 55-76.

A review is given of the effect of large particles (diameter >0.1 - 0.5 μm) and of small particles (diameter <0.1 μm) on the nucleation and growth stages of recrystallization. Parameters discussed are the size and the spacing of particles, the grain size of the matrix and the degree of deformation. Alloys containing large particles are exemplified by aluminium of commercial purity containing $FeAl_3$ particles; alloys containing small particles are exemplified by Al-Al_2O_3 alloys. A number of experimental results obtained in these systems are reported together with literature data for other alloys.

LOWI, a New Zircaloy-UO_2 Fuel Design: Design Considerations, Calculations and Test Results.

A. Jensen, Nucl. Technol. 39 (1978) 283-288.

The performance of present-day Zircaloy-UO_2 fuel design for water cooled reactors has for several years been intensively examined and modelled. The established know-how is used as a background for the suggestion of a new design, named LOWI (Low Interaction), which, by merely introducing a small change in the arrangement of the fuel material, should lead to an improved performance with respect to mechanical interaction and, at the same time should reduce the fuel center temperature and therefore consequently reduce the stored energy.

Considerations that form the basis for the LOWI design are supported by the calculational results of some of the more important aspects. The design has been initially evaluated in an irradiation experiment, and the test results have generally supported the objectives of the design.

Svejsning af Al-tyndplade. (Welding of Thin Al plate).

B.S. Johansen, P. Dreves and J. Olsson, In: Svejsning og Lodning, Proceedings of Dansk Metallurgisk Selskabs Vintermøde, Lyngby, 5-6 January 1978. Edited by E.W. Langer and T.S. Nielsen. (Dansk Metallurgisk Selskab, Lyngby, 1978) 193-201.

The development of welding procedures for 0.5 to 1.5 mm aluminium, as used in the fabrication of fuel elements and irradiation capsules for the Danish DR3 materials testing reactor, are described.

Tests with various welding machines and welding parameters, using AC GTAW (gas tungsten arc welding) with argon as the shielding gas, led to the establishment of satisfactory procedures for the welding of 1.5 mm aluminium. In the course of this development it was found that welding machine parameters, that are not normally stated or measured, such as current and voltage waveforms, had a large influence on the welding process.

0.5 mm aluminium could not reliably be welded with AC GTAW. Tests with pulsed DC-GTAW welding, with helium used as the shielding gas, gave however very good results when combined with a special preparation at the edges to be welded.

Performance Evaluation of UO_2-Zr Fuel In Power Ramp Tests.

P. Knudsen, C. Bagger and N. Kjær-Pedersen, In: Nuclear Power and Its Fuel Cycle. Proceedings of the International Conference on Nuclear Power and Its Fuel Cycle, Salzburg, 2-13 May 1977. Vol. 2. (IAEA, Vienna, 1977) 661-672.

The abstract appeared in the previous progress report p. 40.

Power Ramp and Fission Gas Performance of Fuel Pins M20-1B, M2-2B and T9-3B.

P. Knudsen and C. Bagger, Risø-M-2151 (1978) 32 pp.

Three UO_2-Zr test fuel pins were irradiated together to 24,100 MWD/te UO_2 at heat loads decreasing from 560 to 250 W/cm (average test levels), the latest level being 320 W/cm. One pin was then ramp tested to 420 W/cm and kept there for 550 hrs. without failure indication.

The other two pins were further irradiated to 26,100 MWD/te UO_2 at somewhat lower heat loads, with a latest level of 230 W/cm. Ramp testing to 430 W/cm did not produce failure during a hold-time of 670 hrs.

The paper presents details of design, irradiation, and hot-cell examination.

Water Reactor Fuel Performance.

D.H. Locke, J.H. Gittus, P. Knudsen, J.C. Wood, A. Garlick, Nucl. Energy 17 (1978) 185-204.

A review is given of the papers presented at the ANS Topical Meeting on Water Reactor Fuel Performance, held at St. Charles (Ill.), May 9-11, 1977.

Separation of Rare Earth, Nuclear-Fuel Burn-Up Monitors in the 10^{-9} Mole Range by High-Pressure Liquid Chromatography with UV-Detection.

N.R. Larsen and W.B. Pedersen, J. Radioanal. Chem. 45 (1978) 135-140.

Anion-exchange chromatography of the rare earth (Sm, Nd, Pr, Ce) ions in methanol-nitric acid-water media is performed using high-pressure liquid chromatography. The separation method is especially designed for determination of ^{148}Nd in the nuclear fuel cycle in order to find precise burn-up values. The high-pressure liquid chromatography method presented here is very fast, gives high resolutions, and enables collection of selected fractions containing nmoles of rare earth by UV monitoring at 280 nm of the eluate.

The Activation Energy for Loop Growth in Cu and Cu-Ni Alloys.
P. Barlow, T. Leffers and B.N. Singh, Risø-M-2129 (1978) 18 pp.

The apparent activation energy for the growth of interstitial dislocation loops in copper, Cu-1%Ni, Cu-2%Ni, and Cu-5%Ni during high voltage electron microscope irradiation was determined. The apparent activation energy for loop growth in all these materials can be taken to be $0.34eV^{\pm}0.02eV$. This value together with the corresponding value of $0.44eV^{\pm}0.02eV$ determined earlier for Cu-10%Ni is discussed with reference to the void growth rates observed in these materials. The apparent activation energy for loop growth in copper (and in Cu-1%Ni that has a void growth rate similar to that in pure copper) is interpreted as twice the vacancy migration energy (indicating that divacancies do not play any significant role). For the materials with higher Ni content (in which the void growth rate is much lower than that in Cu and Cu-1%Ni) the measured apparent activation energy is interpreted to be characteristic of loops positioned fairly close to the foil surface and not of loops in "bulk material". From the present results in combination with the earlier results for Cu-10%Ni it is concluded that interstitial trapping is the most likely explanation of the reduced void growth rate in Cu-Ni alloys.

Loop Growth and Point Defect Profiles during HVEM Irradiation.
T. Leffers and B.N. Singh, Risø-M-2142 (1978) 28 pp.

In this work the point-defect profile in the thin foil has been included in the model for the growth of dislocation loops during HVEM irradiation suggested by Kiritani, Yoshida, Takata, and Maehara, and the possible effect of divacancies is discussed. It is found that there is a fairly wide transition range between the two extreme cases described by Kiritani et al. (the vacancy- and the surface-dominant case); this can directly (without the necessity of a divacancy effect) explain the observation of apparent activation energies for loop growth smaller than $1/2\ E_v^M$ (where E_v^M is the vacancy migration energy). Even after the inclusion of the point-defect profiles there are indications that the model cannot fully account for the loop growth behaviour in situations where surface losses and recombination losses are comparable.

Texture Control: Theoretical and Practical Study.

P. Gangli and T. Leffers, In: Textures of Materials, Proceedings of the Fifth International Conference on Textures of Materials, Aachen, 28-31 March 1978. Vol. I. Edited by G. Gottstein and K. Lücke (Springer-Verlag, Berlin, 1978) 209-214.

Control of texture is desirable in a number of materials for a number of applications, and texture control is an established part of industrial practice. Normally, the control is carried out via an appropriate combination of plastic deformation and annealing (recrystallization and/or phase transformation), i.e. no attempt is made to control the deformation texture as such.

In the present work we consider the possibility of controlling or changing the rolling texture by simple modifications to the rolling process (changes of rolling direction according to various schemes). We emphasize the application of computer simulation: it is demonstrated that the computer programs developed for the simulation of the normal rolling textures can also satisfactorily predict the textures formed under the new rolling conditions. Computer simulation could thus be an important tool for deformation-texture control, especially in cases where one considers changes in the deformation pattern that would require modifications to the rolling equipment (so that the resulting texture could not be checked experimentally before the modifications were made).

The Origin of the FCC Rolling-Texture Component with {111} Parallel to the Rolling Plane.

T. Leffers, In: Textures of Materials, Proceedings of the Fifth International Conference on Textures of Materials, Aachen, 28-31 March 1978. Vol. I. Edited by G. Gottstein and K. Lücke (Springer-Verlag, Berlin, 1978) 357-365.

The brass-type rolling texture has a component with {111} parallel to the rolling plane. In normal materials, however, this component is so weak that a direct study is difficult.

The present author has previously shown (Met. Trans. 5 (1974) 2110) that the {111} component is very strong in coarse-grained brass rolled to 80% reduction, i.e. this material is particularly suited for a study of the {111} texture component.

It is shown by electron microscopy that the twin lamellae in such a material are predominently parallel to the rolling plane. The twins are probably, at an earlier stage of deformation, formed on planes with a high resolved shear stress. From this it is concluded that the {111} planes parallel to the rolling plane at 80% reduction have been primary slip planes at an earlier stage, i.e. that they have approached their present orientation by "overshooting". Such overshooting could be explained by the very presence of the twins: the twin lamellae would make slip more difficult on slip planes inclined to the slip plane with twins. It has been shown earlier that mechanical twinning becomes more predominant with increasing grain size, which obviously agrees with the finding that the {111} texture component is particularly strong in coarse-grained materials.

The Shortcomings of the Taylor Model in the Description of the Plastic Deformation of Real Polycrystals.

T. Leffers, In: Textures of Materials, Proceedings of the Fifth International Conference on Textures of Materials, Aachen, 28-31 March 1978. Vol. I. Edited by G. Gottstein and K. Lücke (Springer-Verlag, Berlin, 1978) 277-287.

The Taylor model for the plastic deformation of polycrystals provides an elegant mathematical solution to the problem of material continuity, and for this reason there is a general trend to accept it as the theory for polycrystal plasticity (cf. its widespread application for texture calculations). However, there is another problem in polycrystal plasticity of equal importance, viz. the problem of stress continuity, to which the Taylor theory does not offer any solution.

In the author's opinion the two continuity problems can only be solved simultaneously in a theory that includes the dislocations that produce the plastic deformation.

In the present work the Taylor theory is discussed in terms of the dislocation pattern in real polycrystals. Recent results of computer-simulation studies of the interaction between dislocations and grain boundaries are included in the discussion. The conclusion is that the Taylor theory is not in general compatible with a dislocation-based description of the plastic deformation of polycrystals.

This demonstration of the theoretical shortcomings of the Taylor model is in line with a number of examples of disagreement between experimental findings and deductions from the theory. In the texture field the following examples can be mentioned: the absence of the theoretical Taylor orientation {11 4 4}<8 11 11> in the experimental f.c.c. rolling textures and the observation that experimental rolling textures correspond to superpositions of textures of rolled single crystals.

Work-hardening of Two-Phase Materials.

H. Lilholt, In: High Performance Materials and Processes, Proceedings of the Danish-Israeli Conference, Lyngby, 14-17 August 1978. Edited by E.W. Langer and T.S. Nielsen. (Dansk Metallurgisk Selskab, København, 1978) 89-104.

The theory for the flow stress and the work hardening rate of two-phase materials in the unrelaxed state is quite well established and is supported by many experiments. The relaxation processes and the mechanical behaviour in the relaxed state are less well understood and experiments are more complicated and difficult to interpret.

Kompositmaterialer - egenskaber, fremstilling og anvendelser. (Composite Materials - Properties, Production and Applications).
H. Lilholt, Dansk Tekn. Tidsskr. 102 No. 3 (1978) 10-17.

A review of the status of fibre reinforced materials covers the mechanical and physical properties, the types of fibres and their price, fabrication methods and applications, with several examples from the field of energy technology.

Lodning af aluminium. (Brazing and Soldering of Aluminium).
Aa. Lystrup, In: Skandinaviske Aluminiumdage, held in Copenhagen 13-14 September 1978. (Skanaluminium, Oslo, 1978) paper III 4, 17 pp.

A short general discussion of the basic concepts of brazing and soldering and the special aspects which arise in aluminium brazing is followed by a survey of the most common brazing and soldering methods for aluminium. First dipbrazing in a molten flux bath is discussed as an example of a conventional flux brazing method, and finally there is a discussion of ultrasonic soldering and vacuum brazing which both are a fluxless joining method for aluminium.

Lodning af aluminium. (Brazing and Soldering of Aluminium).
P. Dreves Nielsen, Metal. No. 21 (1978) 15.

A discussion is given of advantages and disadvantages of various methods for soldering and brazing of aluminium.

Transformation Theory for Composites.
O. Bøcker Pedersen, Z. Ang. Mat. Mech. 58 (1978) T227-T228.

The abstract appeared in the previous progress report p. 42.

Transformation Theory for the Physical and Mechanical Properties of Composites.

O. Bøcker Pedersen, In: ICCM/2, Proceedings of the 1978 International Conference on Composite Materials, Toronto, Canada, 16-20 April 1978. (Metallurgical Society of AIME, New York, 1978) 61-62.

A simple expression for the effective compliance matrix of 2-phase particulate and fibrous composites is given. The expression is derived from a mean field model. It is pointed out that the expression reproduces existing variational results for the effective engineering moduli. Parallels to the theory of other effective linear moduli are emphasized.

Kemisk fornikling - en metode med spændende muligheder. (Electroless Nickel Plating - A Method with Interesting Possibilities).

K. Rørbo, Dansk Tekn. Tidsskr. 102 No. 1 (1978) 33-36.

The special features of the electroless nickel plating process are described and possible problems with start of the process and with adhesion to the substrate are mentioned. A number of practical examples where electroless nickel plating has been applied to special surfaces (titanium, molybdenum, alumina, stainless steel wire mesh) are given.

HVEM Studies of Void Formation in Cu-Ni Alloys.

B.N. Singh and T. Leffers, In: High Voltage Electron Microscopy 1977, Proceedings of the 5th International Conference on High Voltage Electron Microscopy, Kyoto, 29 August - 1 September 1977. Edited by T. Imura and H. Hashimoto. (Japanese Society of Electron Microscopy, Tokyo, 1977) 581-584.

The abstract appeared in the previous progress report p. 43.

On Carbide Cracking as a Source of Acoustic Emission in Steel.

W.E. Swindlehurst, J. Mater. Sci. 13 (1978) 209-212.

An experimental investigation of the role of carbide cracking in generating detectable acoustic emission in a spherodised high carbon steel is presented. On the basis of both this investigation and data from the literature, carbide cracking as a source of emission in mild steels is discussed.

Mechanical Properties of Glass Surfaces Coated with Tin Oxide.
W.E. Swindlehurst and B. Cantor, Glass Technology 19 No. 1 (1978) 14-15.

The coating of glass containers is an industrial process aimed at improving the mechanical properties of containers such as bottles and jars. This paper reports an investigation into the effects of tin dioxide sputtered coating on the friction and contact damage properties of silicate glass.

A Model for Acoustic Emission Generation in Composite Materials.
W.E. Swindlehurst and C. Engel, Fibre Science and Technology 11 (1978) 463-479.

A model for the generation of acoustic emission during the micro-fracturing of a brittle phase in a composite material is described. An important feature of the model is that the interaction of the brittle phase with the matrix is specifically considered.

Acoustic Emission from Brittle Solids.
W.E. Swindlehurst, Materialenyt No. 2 (1978) 55-62.

Examples of the use of acoustic emission in detecting crack propagation and failure in industrially important brittle materials are discussed.

Termisk analyse er en nyttig målemetode ved materialeundersøgelser. (Thermal Analysis is a Useful Tool in Materials Research).
O. Toft Sørensen and H. Jensen, Dansk Tekn. Tidsskr. 102 No. 7/8 (1978) 9-11.

The following thermoanalytical techniques are described: Differential Thermal Analysis (DTA), Thermogravimetric Analysis (TG), Simultaneous Analysis (DTA/TG) and Dilatometry. The equipment developed at the Metallurgy Department for these measurements is also discussed and a few examples of the use of this equipment in materials research are given.

Thermogravimetric Studies of Non-Stoichiometric Cerium Oxides under Isothermal and Quasi-Isothermal Conditions.

O. Toft Sørensen, J. Thermal Analysis 13 (1978) 429-437.

The abstract appeared in the previous progress report p. 44.

A Probabilistic Cumulative Damage Procedure for Estimation of Fatigue Life.

R. Talreja, In: Fatigue - Fundamental and Applied Aspects, Proceedings from a Seminar held at Rimforsa, Sweden, 15-18 August 1977. Edited by T. Ericsson. (Linköping Institute of Technology, Linköping, 1978). Not paginated, 13 pp.

A cumulative damage method based on the residual strength as fatigue parameter is presented. The statistical nature of fatigue is accounted for by considering the statistical variation of residual strength in both the crack initiation and the crack propagation stages of fatigue. The predictions of this method for two-amplitude loads are shown to be very accurate and superior to those of Miner's method.

Brint kan erstatte elektricitet og kan opbevares i form af metalhydrider. (Hydrogen can Replace Electricity and can be stored in the Form of Metal Hydrides).

B. Vigeholm, Dansk Tekn. Tidsskr. 102 No. 5 (1978) 11-14.

The potentials of hydrogen-metal systems in the future energy sector is outlined. Some of the forseeable applications are mentioned e.g. hydrogen storage for automotive purposes, hydrogen storage, heat pumping.

Metal-brint i varmesystemer. (Metal-hydrogen in Heat Systems).
B. Vigeholm, In: Energiforskning på Risø, Risø-M-2126 (1978) 105-110.

Hydrogen is sorbed in many metals under liberation of heat. During the reversed process hydrogen is liberated by addition of heat to the metal-hydrogen compound (hydride). This reaction may be used to either liberate or store heat and constitutes a suitable system for combined heat pumping and heat storage plants. The system is operational but so far not economically competitive despite a number of advantages.

Research on Zirconium Hydriding and Palladium Alloy-Hydrogen Systems at Risø National Laboratory.
B. Vigeholm, J. Kjøller, B. Larsen and O. Toft Sørensen, In: Hydrides for Energy Storage, Proceedings of an International Symposium held at Geilo, Norway, 14-19 August 1977. Edited by A.F. Andresen and A.J. Maeland. (Pergamon, Oxford, 1978) 491-499.

The abstract appeared in the previous progress report p. 44.

LECTURES

Results from the Danish LOWI Fuel Experiments.

J. Aukdal and A. Jensen, presented at the Enlarged Halden Programme Group Meeting, Loen, 5-8 June 1978. (Not available).

The Danish LOWI (low interaction) fuel design is in an initial test phase, during which the basic design idea is evaluated. The experimental programme, as outlined in this paper, comprises four individual experiments. The results obtained from this programme support the general design idea.

Utilization of Computer Technology in Combination with Non-Destructive Measurement on Water-Reactor Fuel Rods at Risø.

C. Bagger, presented to the Euratom Hot Cell Working Group, Saclay, Paris, 19 October 1978. (Transcript available,10 pp.).

Risø has carried out post-irradiation examination on nuclear fuels since 1964. Computer technology has recently been applied in non-destructive testing for the automation of data acquisition, data handling, and data reduction. This resulted in an increase in the reliability of the measurements together with a considerably better utilization of the shielded facility where the measurements are carried out. The amount of data of importance for the evaluation is increased, and the speed of evaluation is enhanced because of the possibilities of manipulating scaling factors and curve plots.

Determination of Effective Diffusion Coefficients from Measurements of Creep Incubation Periods.

J.B. Bilde-Sørensen, presented at the Workshop on the Interaction between Dislocations and Point Defects in Oxide Single Crystals, C.N.R.S., Bellevue, 6-9 June 1978. (Not available).

A recently developed model for the phenomena following a stress reduction during creep was discussed. It was pointed out that the effective diffusion coefficient for creep can be derived from measurement of the length of the incubation period following a stress reduction on the basis of this model. Possible applications of the method were discussed.

Fission Gas Release in LWR Fuel Rods Exhibiting Very High Burn-up.

H. Carlsen, presented at the IAEA Technical Committee Specialists' Meeting on "Fuel Element Performance Computer Modelling", Blackpool, 13-17 March 1978. (Manuscript to be published in Nucl. Eng. and Design).

Two UO_2-Zr BWR type test fuel rods were irradiated to a burn-up of about 38000 MWd/tUO_2. After non-destructive characterization, the fission gas released to the internal free volume was extracted and analysed.

The irradiation was simulated by means of the Danish fuel performance code WAFER-2, which uses an empirical gas release model combined with a strongly burn-up dependent correction term, developed by the US Nuclear Regulatory Commission. The paper presents the experimental results and the code calculations.

It is concluded that the model predictions are in reasonable agreement (within 15%) with the experimental results. No similar agreement could be obtained without the burn-up dependency of the release model.

Xenon, Krypton and Helium Release in High Burn-Up UO_2-Zr Fuel Rods.

H. Carlsen, presented at the Workshop on Fission Gas Behaviour, Karlsruhe, 26-27 October 1978. (Proceedings to be published).

Five UO_2-Zr test fuel rods were irradiated to burn-up levels in the range 25000-40000 MWd/t UO_2; three of these rods were exposed to and survived a final ramp testing. The irradiations were simulated by means of the fuel performance code WAFER-3, which uses an empirical fission gas release model, combined with a burn-up-dependent correction term, which is shown to be relevant.

The gas extracted after the irradiation contained a surplus of helium compared to the initial amount, besides the krypton and xenon gases released. This is explained as a result of ternary fission and the α-decay of ^{242}Cm.

Principles of High Temperature Brazing.

J. Christensen, presented at Nordisk Seminar om lodning og varmebehandling af stål i vakuum, Glostrup, 23-24 October 1978. (Not available).

The basis for brazing will be shortly gone over with special reference to the brazing of stainless steels and nickel-chromium alloys:

- cleaning of metals in hydrogen and in vacuum
- different types of furnaces
- alloying and diffusion of filler metals - parent metals.

A short survey of the many possibilities to select filler metals for the brazing of stainless steels and the nickel-chromium alloys will be given. Special attention will be paid to the use of the relatively cheap nickel-based filler metals as problems may arise - due to the formation of inter-metallics, - if these filler metals are not correctly used. The mechanical properties as well as the corrosion resistance of joints brazed with these nickel-based filler-metals are very dependent on the combination of joint design, brazing gap, and brazing cycle (heat treatment).

Dynamic Fracture Toughness Testing of Structural Steels.

C.P. Debel, presented at the OECD-NEA-CSNI Specialist Meeting on "Elasto-Plastic Fracture Mechanics", Warrington, 22-24 May 1978. (Proceedings to be published).

A presentation in English of the Ph.D.-work described in the report Risø-M-1897. The results obtained here are in this paper compared with similar results obtained by other investigators using a variety of structural steels and test methods. Furthermore two new candidate methods for evaluating the dynamic fracture toughness are presented.

Neutron Radiography Activities at Risø National Laboratory.

J.C. Domanus, held at Argonne National Laboratory, Idaho, 28 April 1978 and at Hanford Engineering Development Laboratory, Washington, 1 May 1978. (Not available).

Risø neutron radiography facility at DR 1 was described. The results of the investigation performed on dimension measurements from neutron radiographs were presented. Original X-ray and neutron radiographs of the calibration fuel pin taken on X-ray and nitrocellulose film were shown. Neutron radiography facility and procedure was illustrated by projection of slides from Risø.

LOWI, a New Fuel Design for Water Reactors.

A. Jensen, presented at Nuclex 78, 5th International Fair and Technical Meetings of Nuclear Industries, Basle, 3-7 October 1978. (Not available).

The LOWI (Low Interaction) fuel design is described and the results obtained with this fuel design are discussed.

LOWI-Fuel.

A. Jensen, presented at the IAEA International Symposium on "Water Fuel Element Fabrication with Special Emphasis on its Effect on Fuel Performance", Prague, 6-10 November 1978. (Not available).

The LOWI (Low Interaction) fuel design is described and the results obtained with this fuel design are discussed.

The Nucleation of Recrystallisation in Aluminium Containing Dispersions of Alumina.

A. Jones, B. Ralph and N. Hansen, presented at the Metals Society Conference on "Recrystallisation in the Development of Microstructure", Leeds, 4-6 April 1978. (Manuscript to be published in Met. Sci. J.).

A study has been made of the recrystallisation process in a series of samples of aluminium containing dispersions of oxide particles. The effect of varying the volume fraction of oxide and the initial grain size has been investigated. Both the macroscopic and microscopic aspects of the recrystallisation processes have been evaluated. The results from measurements of hardness, observation by light microscopy and by transmission electron microscopy are in accord.

Nucleation events both within the grains and at intragranular sites have been found. The effect of an increasing volume fraction of oxide particles is to slow down both the formation and growth of viable nuclei.

Early-Life WAFER-2 Analyses of Selected IFA Experiments.

N. Kjær-Pedersen and E. Kolstad, presented at the Enlarged Halden Programme Group Meeting, Loen, 5-8 June 1978. (Not available).

Several rod histories from a series of IFA thermocouple experiments have been analysed by means of the Danish WAFER-2 code. The experiments represent a variety of as fabricated gap-sizes, pressurized and non-pressurized rods, and heat-ratings up to 500 W/cm. Further, the first cycle of the history of one rod from the diameter rig has been analysed for the purpose of studying ridge formation.

WAFER-2. A Code for Thermal and Mechanical LWR Fuel Performance Modelling.

N. Kjær-Pedersen, presented at the IAEA Technical Committee Specialists' Meeting on "Fuel Element Performance Computer Modelling", Blackpool, 13-17 March 1978. (Manuscript to be published in Nucl. Eng. and Design).

This paper gives a brief description of WAFER-2 and reports on the application of the model to a well-documented experimental case of severe ridging. It is demonstrated that the code predictions, especially regarding ridge heights, are in good agreement with the observed values, the code concepts thereby being verified.

Ramp Testing of High-Burn-Up UO_2-Zr Fuel Pins.

P. Knudsen and C. Bagger, presented at the Enlarged Halden Programme Group Meeting, Loen, 5-8 June 1978. (Not available).

Three UO_2-Zr test fuel pins were irradiated together to 2330 GJ/kg U (23,800 MWD/te UO_2) at heat loads decreasing from 50 to 24 kW/m (500 to 240 W/cm) (test average levels), the latest being 31 kW/m (310 W/cm). One pin was then power ramped to 45 kW/m (450 W/cm) at 35 W/m·s (21 W/cm·min.) and kept there for 2 Ms (550 hrs.) without failure indication.

The other two pins were further irradiated to 2450 GJ/kg U (25,000 MWD/te UO_2) at approximately 23 kW/m (230 W/cm). Ramp testing to 43 kW/m (430 W/cm) did not produce failure during 2.4 Ms (670 hrs.).

The fission gas release in the three pins was 30-40%. A limited metallographic examination revealed extensive fuel-clad reaction.

Design and irradiation details are included for use as input in the validation of fuel performance codes.

Eksperimenter og driftserfaringer med brændsel til kernekraftværker. (Experiments and Performance Experience with Fuel for Nuclear Power Reactors).

P. Knudsen, presented to Dansk Kerneteknisk Selskab, Copenhagen, 30 January 1978. (Not available).

The general performance experience with UO_2-Zr fuel for water-cooled power reactors is summarized. Problem areas are discussed and illustrated, including examples from the Danish irradiation program.

Teoretiske and praktiske aspekter af brændselselementers metallurgi. (Theoretical and Practical Aspects of the Metallurgy of Nuclear Fuel Elements).

T. Leffers and P. Knudsen, presented to Dansk Metallurgisk Selskab, Lyngby, 18 April 1978. (Not available).

Metallurgical aspects of the performance of nuclear fuel are illustrated by means of examples from the theoretical and experimental work at Risø, such as: (i) the swelling of stainless steel claddirg due to void formation in fast breeder reactors, (ii) pellet-clad interaction in UO_2-Zr fuel for thermal reactors.

The Annealing of Neutron-Irradiated Copper Studied by Positron Annihilation Techniques (PAT) and Transmission Electron Microscopy (TEM).

O.E. Mogensen, M. Eldrup, B.N. Singh and J.H. Evans, presented at Dansk Fysisk Selskabs Forårsmøde 1978, Helsingør, 15-16 Juni 1978. (Not available).

PAT- and TEM-measurements have been made during the isochronal annealing of copper. In a preliminary work the samples were neutron irradiated to a dose of 5×10^{18} fast neutrons/cm^2 at 50°C. Marked changes in the PAT-parameters took place in the irradiation; these changes annealed out in a sharp recovery stage between $\sim$ 300 and 400°C. We then neutron irradiated copper at $\sim$ 255°C to doses of 5×10^{17} and 1×10^{18} fast neutrons/cm^2, which resulted in the formation of voids. The PAT-parameters indicated annealing stages at $\sim$ 280°C (probably vacancy loop annealing) and at $\sim$ 450°C (probably void annealing). The PAT-results are correlated to TEM-studies of identical samples. PAT-studies give information on small polyvacancies (voids) of size $\lesssim$ 15 Å which cannot be resolved by use of TEM. Voids are important radiation damage in reactor technology (fission and fusion).

Interpretation of Quasi-Isothermal Thermogravimetric Weight Curves.

O. Toft Sørensen, presented at the GEFTA/NSTA Symposium on Thermal Analysis, Kiel, 6-9 September 1978. (Manuscript to be published in Thermochim. Acta).

Quasi-isothermal analysis (QIA) is a very useful technique. Compared to conventional non-isothermal thermogravimetry, closelying reactions can easily be separated by use of this method and kinetic data can be obtained for each intermediate reaction in a single run. This paper discusses the shape of the weight and temperature curves expected in QIA for different controlling mechanisms, and a method is given for calculating the activation energies from these curves. As an example, the QIA curves obtained in thermal decomposition of ammonium-uranyl carbonate (AUC) are analysed and the kinetics of some of the intermediate reactions are determined.

Thermal Analysis of the Reduction of Ammonium Uranyl Carbonate.

L. Hälldahl and O. Toft Sørensen, presented at the GEFTA/NSTA Symposium on Thermal Analysis, Kiel, 6-9 September 1978. (Manuscript to be published in Thermochim. Acta).

The intermediate products formed during thermal decomposition of ammonium uranyl carbonate (AUC) in different atmospheres (air, helium and hydrogen) have been determined by thermal analysis (TG and DTA) and X-ray analysis. The end products observed are U_3O_8 and UO_2 in air/He and hydrogen, respectively, whereas the following intermediate products were observed in all atmospheres: $UO_3(H_2O)_{1,5}$; $UO_3(H_2O)$; $UO_3(H_2O)_{0,65}$; $UO_3(H_2O)_{0,5}$ and $UO_2(H_2O)_{0,25}$. X-ray diffraction analyses showed that these phases were amorphous. A model for the reaction pattern of AUC-particles under industrial conditions is also presented in the paper.

Materialeundersøgelser ved hjælp af termisk analyse. (Thermal Analysis in Materials Research).

O. Toft Sørensen and H. Jensen, held at Statsprøveanstalten, København, 10 February 1978. (Not available).

The principle and examples of measurements carried out with the different thermoanalytical methods developed at the Metallurgy Department were discussed in the lecture.

Undersøgelser af termodynamiske egenskaber og defektstrukturer i ikke-støkiometriske oxider med termisk analyse. (Examination of Thermodynamical Properties and Defect Structures in Non-Stoichiometric Oxides by Thermal Analysis).

O. Toft Sørensen, held at Norges Tekniske Højskole, Trondheim, 13 January 1978. (Not available).

Thermodynamic data determined by thermogravimetric measurements in controlled atmospheres on non-stoichiometric oxide systems (CeO_{2-x}, PuO_{2-x} and $(U,Pu)O_{2-x}$) was discussed in the lecture. A detailed analysis of these data shows that the non-stoichiometric phase range can be devided into subregions each with a characteristic defect structure. The existence of these subregions has also been verified by statistical thermodynamic calculations, which also was discussed.

Introduction to Thermogravimetry.

O. Toft Sørensen, presented at the Symposium on "Thermoanalysis in Theory and Practice", Stockholm, 14-15 June 1978. (Transcript available 14 pp.).

Thermogravimetry (TG) is one of the most important members of the larger family of thermal analysis techniques. In the lecture modern thermobalances and the different techniques were described as well as the influence of the most important parameters to be considered in thermogravimetric measurements. Finally the Organization of Thermal Analysis both in the Scandinavian countries and internationally was also described in the lecture.

Metal-brint i varmesystemer (Metal-hydrogen in Heat Systems).

B. Vigeholm, presented to Ingeniørsammenslutningens VVS-gruppe, Risø, 28 November 1978. (Manuscript published in Risø-M-2126).

Hydrogen is sorbed in many metals under liberation of heat. During the reversed process hydrogen is liberated by addition of heat to the metal-hydrogen compound (hydride). This reaction may be used to either liberate or store heat and constitutes a suitable system for combined heat pumping and heat storage plants. The system is operational but so far not economically competitive despite a number of advantages.

Lagring i metal-brint systemer. (Storage in Metal-Hydrogen Systems).

B. Vigeholm, presented to Dansk V.V.S. Teknisk Forenings Solenergigruppe, Lundtofte, 13 March 1978. (Not available).

Many metals readily sorb hydrogen according to the reaction: metal + hydrogen ↔ metalhydride + heat. The process is reversible. Hydrogen added to the metal is sorbed under liberation of heat, and if heat is now added the reaction is reversed and hydrogen is liberated.

One of the more promising applications of the hydride-technology is storage of energy from renewable sources like sun and wind. The solar heat is added to a metalhydride liberating hydrogen which may be stored in a pressure tank. When the heat is required a valve is opened and the hydrogen will be resorbed in the metal and heat released.

Opbevaring af energi i metalhydrider. (Storage of Energy in Metal Hydrides).

B. Vigeholm, presented to Danske Forsyningsselskabers Funktionærsammenslutning, 28 October 1978. (Not available).

In metal-hydrogen systems energy may be stored either as hydrogen or as binding energy. The principle of system performance and some applications is described, with emphasis on energy capacity and cost relative to other systems.

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